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Observations and modeling of the massive young star AFGL 4176: From large scales to small

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Abstract. We present spatially-resolved mid-infrared interferometric observations of the massive young stellar object AFGL 4176, together with literature and survey data. We model these observations using a simple, spherically-symmetric radiative transfer model, and find that the observational data are consistent with a highly luminous star surrounded by a thick envelope.

1. Introduction

Massive stars in the act of formation are a rare phenomenon in our galaxy. Characterization of these stars, in the form of massive young stellar objects (MYSOs), is required to constrain formation and evolution scenarios. However, any successful observational strategy must account for the inherently large distances (several kpc) and extremely high extinctions ($A_V \sim 100$ mag) involved. Finally, interpretation of observations almost universally requires the construction or adaption of an underlying model.

In an effort to understand such objects better, many authors attempt to reproduce the spectral energy distribution (SED) without accounting for the spatial distribution of emission, as spatially-resolved observations are often not available. However, such an approach is highly degenerate (e.g. Men'shchikov & Henning 1997). Here, we combine extensive multi-wavelength observations with numerical radiative transfer modeling for a single MYSO candidate, AFGL 4176. Our approach encompasses both spectral information in the form of the spectral energy distribution (SED), and spatial information in the form of mid-infrared interferometric visibilities and resolved imaging at far-infrared and sub-millimeter wavelengths.

AFGL 4176 (also known as IRAS 13395-6153, G308.9+0.1) was identified by Henning et al. (1984) as a candidate MYSO based on the similarity of the far-infrared spectrum to that of the Becklin-Neugebauer (BN) object in Orion. However, this object differs from other BN-type objects by virtue of the extremely high luminosity of the central source, with previous works based on SED-fitting suggesting the luminosity is on the order of $10^5 L_\odot$ (Guertler et al. 1991; Grave & Kumar 2009). From 1.2 mm continuum measurements, Beltrán et al. (2006) estimated a gas + dust mass of $1120 M_\odot$. Regarding the evolutionary status of AFGL 4176, a search for an outflow by De Buizer et al. (2009) was inconclusive, although an ultra-compact H II region is present (e.g. Phillips et al. 1998). To date, no compelling evidence for the presence of an accretion disk has been presented.

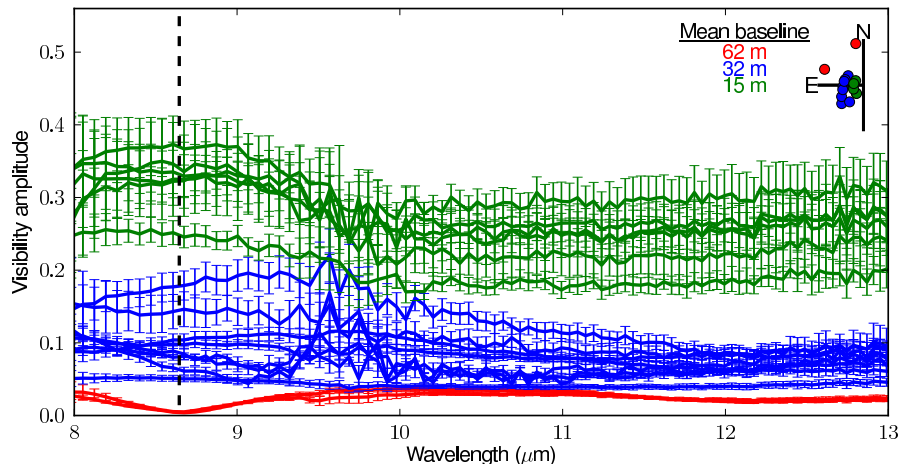


Figure 1. Visibility amplitudes from MIDI. Measurements are colored by projected baseline length, and the locations in UV space are shown in the top right. The dashed line shows the location of the zero crossing observed at long baselines (red).

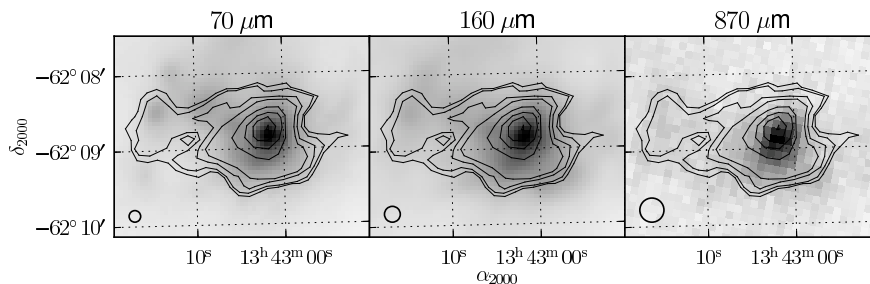


Figure 2. Far-IR and sub-mm images of the region around AFGL 4176 from the Hi-Gal and ATLASGAL surveys. The contours show the 1.2 mm emission, and the circles show the approximate FWHM beam sizes. See text for details.

The distance to AFGL 4176 remains uncertain, as the combination of V_{LSR} for the source and galactic coordinates are forbidden in most galaxy rotation curves. However, for the purpose of this work, we adopt a distance of 3200 pc (A. V. Loktin, private communication).

2. Observations

We observed AFGL 4176 as part of a guaranteed time for observations program using the two-telescope mid-infrared interferometer MIDI on the Very Large Telescope of the European Southern Observatory. We present 19 spectrally-resolved visibility measurements in the N band (8 – 13 μm), obtained in the period from 2005 to 2007, which we show in Fig. 1. The projected baselines span from 13 to 62 m, which corresponds to spatial scales $\lambda/2B$ of about 50 to 250 AU.

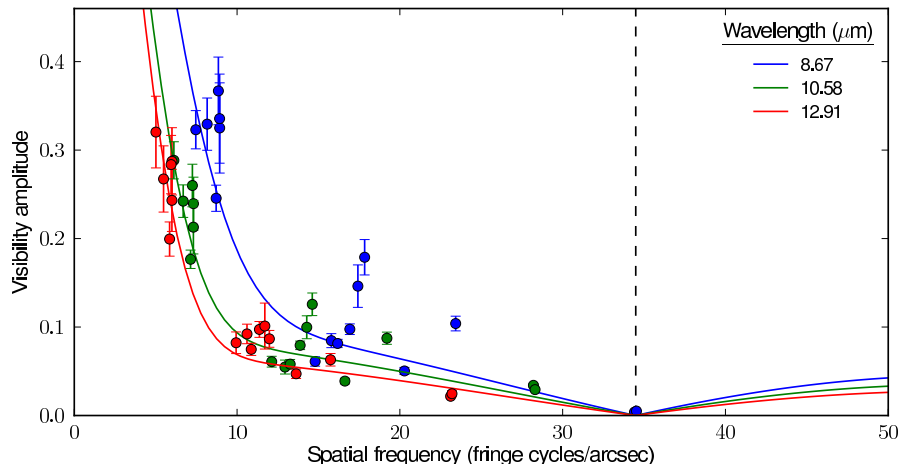


Figure 3. Geometric fits to the visibility amplitudes at three different wavelengths. The dashed line indicates the spatial frequency where the zero crossing is observed.

In Fig. 2, we present images of the region at 70 and 160 μm , obtained with the Herschel space telescope as part of the Hi-Gal program (Molinari et al. 2010), and at 870 μm , obtained with the Atacama Pathfinder EXperiment (APEX) telescope as part of the ATLASGAL survey (Schuller et al. 2009). The source is resolved at these three wavelengths, though shows little structure. For comparison, we have overlaid contours of the 1.2 mm emission measured by Beltrán et al. (2006), obtained with the Swedish-ESO Sub-millimeter Telescope (SEST).

3. Geometric models of N -band visibilities

On two equivalent projected baselines (62 m; red lines in Fig. 1) at position angles differing by 63 deg, we observe a zero crossing in the visibility amplitudes accompanied by a phase flip in the differential phase (not presented). This phenomenon, marked with a dashed line in Fig. 1, not only implies the presence of some sort of hard “edge” in the source intensity distribution, but also suggests that the source is circularly symmetric on the smallest scales probed by our observations.

We attempt to model this behavior with a simple, circularly-symmetric geometric model, consisting of a Gaussian and a thin ring. Using the spatial frequency of the zero-crossing as a constraint for the size of the ring, we find that the observed visibilities can be roughly reproduced by a 100 mas (~ 300 AU) extended component combined with a compact, 10 mas (~ 30 AU) ring-like component. We show the results of this geometric fit in Fig. 3.

4. Radiative transfer modeling

We model the observational data (SED, MIDI visibilities, far-infrared and sub-mm radial intensity profiles) from near-IR through mm wavelengths using a one-dimensional radiative transfer code. We employ a simple dust model consisting of opacities from

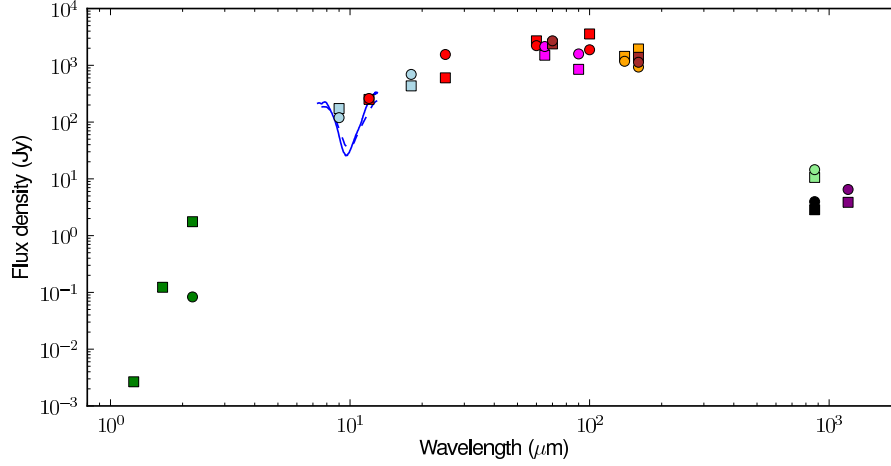


Figure 4. Comparison of the radiative transfer model fluxes (circles and dashed line) to observations (squares and solid line). Aperture and beam sizes for the measurements have been taken into account. In nearly all cases, error bars are smaller than the marker size.

Ossenkopf & Henning (1994) for the cold dust ($T_{\text{dust}} < 130$ K). For the remaining dust ($T_{\text{dust}} \geq 130$ K), we use a 60%/40% mix of astronomical silicates and graphite with an MRN size distribution, using opacities from Laor & Draine (1993).

We find that a piecewise power law for the density distribution is able to adequately reproduce the SED, mid-IR visibilities and far-IR/sub-mm spatial intensity profiles. Around a 15 000 K black body central source with a luminosity of $1.4 \times 10^5 L_{\odot}$, we have an envelope with a dust mass of $5.2 M_{\odot}$. The dust density distribution $\rho(r)$ consists of a hot inner shell with enhanced density, spanning from 40 to 65 AU, surrounded by an extended envelope out to 125 000 AU, with a change in the density falloff at 70 000 AU:

$$\rho(r) = \begin{cases} \left(2.6 \times 10^{-18} \text{ g cm}^{-3} \right) \left(\frac{40 \text{ AU}}{r} \right)^{1.8} & 40 \text{ AU} < r \leq 65 \text{ AU} \\ \left(3.9 \times 10^{-22} \text{ g cm}^{-3} \right) \left(\frac{70\,000 \text{ AU}}{r} \right)^{1.0} & 65 \text{ AU} < r \leq 70\,000 \text{ AU} \\ \left(3.9 \times 10^{-22} \text{ g cm}^{-3} \right) \left(\frac{70\,000 \text{ AU}}{r} \right)^{0.5} & 70\,000 \text{ AU} < r \leq 125\,000 \text{ AU} \end{cases}$$

Our model fit to the SED is shown in Fig. 4, where the effects of aperture and beam sizes on the measured flux levels have been accounted for. The resulting visibilities and the PSF-convolved radial intensity profiles at 70, 160 and 870 μm are shown in Fig. 5. On the whole, the SED and radial profiles can be reproduced well by a spherical model. Near-infrared fluxes are underestimated (similar to the models of Guertler et al. (1991) and Siebenmorgen (1993)), and this may be a fundamental limitation of a spherical model. Despite the simplicity of the density structure used, the model visibility amplitudes match observations rather well. However, a better fit may be possible with a more complex density structure at scales of ~ 100 AU.

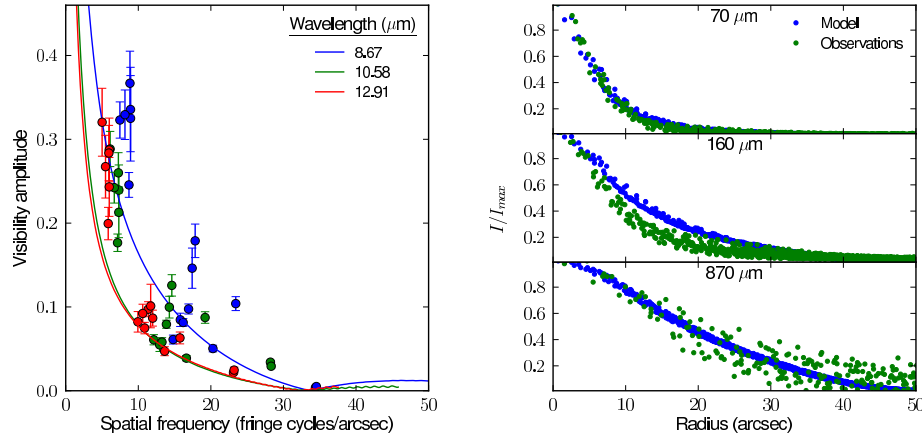


Figure 5. *Left:* Radiative transfer model visibilities (lines) and observed MIDI visibilities (points) at three selected wavelengths. *Right:* Spatial profiles from the radiative transfer model (blue points) compared with observations from Herschel and APEX (green points).

5. Summary and conclusion

We have simultaneously fit the SED and spatial structure at both large (10^5 AU) and small (10^1 AU) scales of the massive young stellar object AFGL 4176 using a spherical radiative transfer model and an appropriate dust model. The simple density structure used and spherical geometry are enough to reproduce many spectral and spatial details in the observations of AFGL 4176.

In the present case, there are no clear signs of significant deviations from spherical symmetry. However, whether this is the result of a face-on orientation or indicative of a true spheroidal nature remains untested. In particular, the physical nature of the density discontinuity at ~ 65 AU could be quite different than presented here (e.g. cool material shaded by the rim of a disk).

Finally, we emphasize that *only* when spatially-resolved observations (at both large and small scales) are combined with SED data may we derive the true physical structure of such objects, whereas modeling of the structure based on SED data alone is degenerate. However, the uniqueness (or ubiquity) of a possible model is nonetheless a strong function of spatial coverage.

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